

## **THEREFORE WHAT IS CLAIMED IS:**

1. A non destructive method for characterizing electronic properties of materials, comprising the steps of:

(a) irradiating at least one surface of a material with an energy beam output from a modulated or pulsed excitation source wherein a recombination-induced infrared emission is responsively emitted from the material;

(b) filtering Planck-mediated thermal emissions from the recombination-induced infrared emission to produce a filtered recombination-induced infrared emission;

(c) detecting said filtered recombination-induced infrared emission; and

(d) calculating selected electronic properties of the material by one of

i) fitting the detected filtered recombination-induced infrared emission to a theoretical model of the photocarrier response of the irradiated material to calculate selected properties of the material, and

ii) using suitable calibration charts or tables to extract selected electronic properties of the material by comparison of the detected filtered recombination-induced infrared emission with reference detected filtered recombination-induced infrared emissions from reference materials with known properties.

2. The method according to claim 1 wherein the step of irradiating at least one surface of the material with an energy beam includes irradiating one surface of the material which generates a carrier-density wave in the material which upon recombination generates the recombination-induced infrared emission.

3. The method according to claim 2 including focussing the energy beam to a pre-selected size on at least one surface, and spatially scanning the focussed energy beam laterally across at least one surface of the material and calculating therefrom maps of any inhomogeneities or defects that affect carrier density, either by enhancing recombination or altering diffusion coefficients, and wherein the theoretical model includes an effective carrier diffusion model to obtain quantitative values for the selected properties of the material, and combining quantitative results of the theoretical model with maps produced from spatial scanning across at least one surface of the material to provide quantitative imaging of the material.

4. The method according to claim 3 wherein the selected properties calculated from the theoretical model include carrier recombination lifetime,  $\tau$ , carrier diffusivity,  $D$ , surface recombination velocities,  $S$ , carrier diffusion lengths,  $L$ , and carrier mobility,  $\mu$ , and space charge layer width,  $W$ .

5. The method according to claim 1 wherein the step of irradiating the material with an energy beam includes irradiating a first surface of the material with a first energy beam to generate a first carrier-density wave and irradiating a second surface of the material opposed to the first surface of the material with a second energy beam to generate a second carrier-density wave with the first and second energy beams being output from optical excitation sources modulated at identical frequencies with the second energy beam having a phase lag of 180 degrees with respect to the first energy beam, and wherein the intensity of the first excitation source focused on the first surface of the material is adjusted to ensure destructive interference of the two carrier-density waves and to give a zero baseline signal.

6. The method according to claim 5 including scanning the first and second energy beams laterally across the material, or moving the material between the first and second energy beams, and detecting for non-zero signals, wherein any inhomogeneities or defects present in the material alter the diffusion, either by enhancing recombination or altering diffusion coefficients, of one or both of the photogenerated carrier density waves which no longer interfere destructively and thus produce a non-zero signal, and calculating therefrom maps of any inhomogeneities or defects that affect carrier density, and wherein the theoretical model includes an effective carrier diffusion model to obtain quantitative values for the selected properties of the material, and combining quantitative results of the theoretical model with maps produced from spatially scanning across at least one surface of the material to provide quantitative imaging of the material.

7. The method according to claim 6 wherein the selected properties calculated from the theoretical model include carrier recombination lifetime,  $\tau$ , carrier diffusivity,  $D$ , surface recombination velocities,  $S$ , carrier diffusion lengths,  $L$ , and carrier mobility,  $\mu$ , and space charge layer width,  $W$ .

8. The method according to claim 1 wherein the excitation source is an optical excitation source pulsed in time domain.
9. The method according to claim 1 wherein the excitation source is an optical excitation source modulated in frequency domain.
10. The method according to claim 1 wherein said excitation source is a laser.
11. The method according to claim 4 wherein the excitation source is a laser modulated at a modulation frequency, including scanning the modulation frequency in a pre-selected range, and wherein the theoretical model includes an effective carrier diffusion model to calculate the selected properties of the material irradiated with a modulated laser, and combining quantitative results of the theoretical model with maps produced from spatially scanning across at least one surface of the material to provide quantitative imaging of the material.
12. The method according to claim 4 wherein the excitation source is a laser pulsed for a given time duration, including scanning the time duration of the pulses in a pre-selected range, and wherein the theoretical model includes an effective carrier diffusion model to calculate the selected properties of the material irradiated with a pulsed laser, and combining quantitative results of the theoretical model with maps produced from spatially scanning across at least one surface of the material to provide quantitative imaging of the material.
13. The method according to claim 6 wherein the excitation source is a laser modulated at a modulation frequency, including scanning the modulation frequency in a pre-selected range, and wherein the theoretical model includes an effective carrier diffusion model to calculate the selected properties of the material irradiated with a modulated laser, and combining quantitative results of the theoretical model with maps produced from spatially scanning across at least one surface of the material to provide quantitative imaging of the material.
14. The method according to claim 6 wherein the excitation source is a laser pulsed for a given time duration, including scanning the time duration of the pulses in

a pre-selected range, and wherein the theoretical model includes an effective carrier diffusion model to calculate the selected properties of the material irradiated with a pulsed laser, and combining quantitative results of the theoretical model with maps produced from spatially scanning across at least one surface of the material to provide quantitative imaging of the material.

15. The method according to claim 4 wherein the maps produced from scanning at least one surface of the material is combined with calibration curves to provide quantitative imaging of the material.

16. The method according to claim 6 wherein the maps produced from scanning at least one surface of the material is combined with calibration curves to provide quantitative imaging of the material.

17. The method according to claim 10 wherein the laser is a solid state laser.

18. The method according to claim 17 wherein said solid state laser is modulated by current modulation.

19. The method according to claim 10 wherein the laser is a gas laser.

20. The method according to claim 1 wherein the excitation source is one of an electron beam source, a flashlamp, a light emitting diode (LED), or any other electromagnetic wave source, which produces a photon beam having sufficient energy to excite carriers in the semiconductor or optical material.

21. The method according to claim 1 wherein the excitation source is modulated by one of a mechanical chopper, an acousto-optic modulator and an electro-optic modulator.

22. The method according to claim 1 wherein the excitation source is a pulsed laser with short duration optical pulses triggered by an internal or external electronic control circuit.

23. The method according to claim 1 wherein the step of detecting the emitted recombination-induced infrared emission is accomplished using one of a room temperature solid state detector, a cooled solid state detector.
24. The method according to claim 1 wherein the step of detecting the emitted recombination-induced infrared emission includes using an imaging array sensor to rapidly image a large surface area of the surface of the material.
25. The method according to claim 1 wherein the step of filtering Planck-mediated thermal emissions from the recombination-induced infrared emission is accomplished using a coated optical window made of material transparent in the spectral range of about 1-3 microns.
26. The method according to claim 1 wherein the step of filtering is accomplished using a solid state detector with detectivity spectrum suitable for eliminating any sensitivity to the incident optical source radiation and to the Planck-mediated thermal emissions while retaining sufficient detectivity in the spectral range of 0.7-3 microns, or another spectral range suitable for semiconductors of higher or lower bandgap energies than that of silicon wafers.
27. The method according to claim 1 wherein the material is selected from the group consisting of semiconductor materials, optical materials and luminescent materials.
28. The method according to claim 27 wherein the energy beam has an energy equal to or greater than a bandgap energy for raising electrons from a valence energy band to a conduction band for producing photo-generated carriers in the semiconductor material or the optical material.
29. The method according to claim 27 wherein the energy beam has an energy equal to or greater than an energy difference between an energy of a bottom of a conduction band and energy levels in a bandgap associated with dopants, impurity atoms or defects for raising electrons from said energy levels in the bandgap to said

conduction energy band for producing photo-generated carriers in the semiconductor material or excited quantum states in the optical material.

30. The method according to claim 27 wherein the semiconductor material includes a scribeline structure on a processed wafer separating device and chip arrays, and wherein probing along the scribeline obtains measurements of signal levels which depend on minority-carrier recombination lifetimes.

31. The method according to claim 27 wherein the semiconductor material includes a layered epitaxial structure, and wherein a dopant uniformity and concentration of the layered epitaxial structure is monitored.

32. The method according to claim 27 wherein the semiconductor material includes ion implanted dopants, and wherein implantation parameters including energy, dose and junction depth can be measured by either fitting the emitted signals to suitable theoretical models or through use of calibration curves.

33. The method according to claim 27 wherein the semiconductor material includes heavy metal contamination, and wherein the contamination can be measured qualitatively by suitable signal contrast between contaminated and uncontaminated regions or quantitatively by either fitting the emitted signals to appropriate theoretical models or through use of calibration curves.

34. The method according to claim 27 wherein the semiconductor material include p-n junction devices formed therein or oxide-semiconductor interfaces.

35. The method according to claims 26 wherein the material includes at least one oxide layer, and wherein one of the selected electronic properties includes calculating a space charge layer width formed by charge concentration in the oxide layer which can be used to calculate a charge concentration and degree of band-bending at the oxide-semiconductor interface, using a suitable theoretical model.

36. The method according to claims 26 wherein the non destructive optical method for characterizing electronic properties of materials is performed on production line in which the material is processed into a product.
37. The method according to claim 36 wherein the material is a semiconductor, and wherein the production line is a semiconductor wafer production line or a semiconductor chip fabrication line.
38. The method according to claim 1 wherein the material is placed on an effective backing material to enhance the recombination-induced infrared emission from the material.
39. The method according to claim 38 wherein the backing material is an infrared reflector material.
40. The method according to claim 1 wherein the excitation source is modulated at a pre-selected modulation frequency, including heating the material suitably and rapidly wherein the detected filtered recombination-induced infrared emission is monitored at the pre-selected modulation frequency such that thermal emissions occurring from a defect or impurity state in the material produce a peak in a temperature scan when the material temperature is such that the thermal energy due to heating the material forces trapped carriers to evacuate their trap states at a rate simply related to the pre-selected modulation frequency, and wherein the energy of the impurity or defect deep level is extracted from the PCR peaks in a series of temperature scans at fixed frequencies using a simple Boltzmann factor, and the PCR signal magnitude is a measure of the occupation density of the level.
41. The method according to claim 1 wherein the excitation source is modulated at a pre-selected modulation frequency, wherein the detected filtered recombination-induced infrared emission is monitored at a pre-selected temperature and the frequency is scanned, wherein thermal emissions occurring from a defect or impurity state in the material produce a peak in the frequency scan when the modulation frequency is approximately equal to a rate of forcing trapped carriers to evacuate their trap states at the pre-selected temperature, and wherein, the pre-selected modulation

frequency is scanned for different (fixed) temperatures and an energy of the level is obtained from an Arrhenius plot of modulation period times  $T_{\max}^2$  vs.  $1/T_{\max}$  using the temperature values,  $T_{\max}$ , of the thermal-emission-induced PCR infrared emission peak occurring at each frequency scan.

42. An apparatus for non destructive characterization of electronic properties of materials, comprising;

a) excitation source means for irradiating at least one surface of a material with energy beams from the optical excitation source means wherein a recombination-induced infrared emission is responsively emitted from the material, the excitation source means being a modulated or pulsed optical excitation source means;

b) filtering means for filtering Planck-mediated emissions from the recombination-induced infrared emission to produce a filtered recombination-induced infrared emission;

c) detection means for detecting the filtered recombination-induced infrared emission;

d) processing means for one of

i) fitting the detected filtered recombination-induced infrared emission to a theoretical model of the photocarrier response of the irradiated material to calculate selected properties of the material, and

ii) comparing the detected filtered recombination-induced infrared emission with reference detected filtered recombination-induced infrared emissions from reference materials with known properties.

43. The apparatus according to claim 42 including means for heating the sample suitably and rapidly wherein the detected filtered recombination-induced infrared emission is monitored at a suitable frequency such that thermal emissions occurring from a defect or impurity state in the material produce a peak in the temperature scan when the material temperature is such that the thermal energy forces trapped carriers to evacuate their trap states at a rate simply related to the suitable frequency, and wherein the energy of the level of the defect or impurity state is obtained from an Arrhenius plot of the lifetime times  $T^2$  vs.  $1/T$  using the temperature values of the PCR peaks at each frequency.



44. The apparatus according to claim 43 wherein the selected properties calculated from the theoretical model include carrier recombination lifetime,  $\tau$ , carrier diffusivity,  $D$ , surface recombination velocities,  $S$ , carrier diffusion lengths,  $L$ , and carrier mobility,  $\mu$ , and space charge layer width,  $W$ .

45. The apparatus according to claim 42 including focussing means for focussing the energy beam to a pre-selected spot size on the at least one surface, and including spatial scanning means for spatially scanning the focussed energy beam across the at least one surface of the material, and wherein the theoretical model calculates from the spatial scans maps of any inhomogeneities or defects that affect carrier density, either by enhancing recombination or altering diffusion coefficients, and wherein the theoretical model includes an effective carrier diffusion model to obtain quantitative values for the selected properties of the material, and wherein the processing means combines quantitative results from the theoretical model or calibration curves with the maps to provide quantitative imaging of the material.

46. The apparatus according to claim 45 wherein the selected properties calculated from the theoretical model include carrier recombination lifetime,  $\tau$ , carrier diffusivity,  $D$ , surface recombination velocities,  $S$ , carrier diffusion lengths,  $L$ , and carrier mobility,  $\mu$ , and space charge layer width,  $W$ .

47. The apparatus according to claim 42 wherein the excitation source means for irradiating at least one surface of a material with an energy beam includes means for irradiating two opposed surfaces of the material for producing a first energy beam irradiating a first side of the material to generate a first carrier-density wave in the material and for producing a second energy beam irradiating a second surface of the material opposed to the first surface of the material to generate a second carrier-density wave in the material, with the first and second energy beams being focussed onto the same position but from opposite sides of the material so that the first and second carrier waves generated in the material are aligned opposite to each other, including modulation means for modulating the first and second energy beams at substantially identical frequencies with the second energy beam having a phase lag of 180 degrees with respect to the first energy beam, and including intensity adjustment means for adjusting an intensity of the first energy beam focused on the first surface

of the material to ensure destructive interference of the two carrier-density waves and to give a substantially zero baseline signal.

48. The apparatus according to claim 47 including focussing means for focussing the first and second energy beams to a pre-selected spot size on the first and second opposed surfaces, and including scanning means for scanning the first and second energy beams laterally across the material, or moving the material between the first and second energy beams, and wherein the detection means detects for non-zero signals, wherein any inhomogeneities or defects present in the material alter the diffusion, either by enhancing recombination or altering diffusion coefficients, of one or both of the photogenerated carrier density waves which no longer interfere destructively and thus produce a non-zero signal, and the processing means calculating therefrom maps of any inhomogeneities or defects that affect carrier density, and wherein the theoretical model includes an effective carrier diffusion model to obtain quantitative values for the selected properties of the material, and wherein the processing means combines quantitative results of the theoretical model with maps produced from spatially scanning across the first and second opposed surfaces of the material to provide quantitative imaging of the material.

49. The apparatus according to claim 48 wherein the selected properties calculated from the theoretical model include carrier recombination lifetime,  $\tau$ , carrier diffusivity,  $D$ , surface recombination velocities,  $S$ , carrier diffusion lengths,  $L$ , and carrier mobility,  $\mu$ , and space charge layer width,  $W$ .

50. The apparatus according to claim 42 wherein the excitation source is an optical excitation source pulsed in time domain.

51. The apparatus according to claim 42 wherein the excitation source is an optical excitation source modulated in frequency domain.

52. The apparatus according to claim 42 wherein said excitation source is a laser.

53. The apparatus according to claim 48 wherein the excitation source is a laser modulated at a modulation frequency, including scanning the modulation frequency in

a pre-selected range, and wherein the theoretical model includes an effective carrier diffusion model to calculate the selected properties of the material irradiated with a modulated laser, and combining quantitative results of the theoretical model with the maps produced from spatially scanning across at least one surface of the material to provide quantitative imaging of the material.

54. The apparatus according to claim 48 wherein the excitation source is a laser pulsed for a given time duration, including scanning the time duration of the pulses in a pre-selected range, and wherein the theoretical model includes an effective carrier diffusion model to calculate the selected properties of the material irradiated with a pulsed laser, and combining quantitative results of the theoretical model with maps produced from spatially scanning across at least one surface of the material to provide quantitative imaging of the material.

55. The apparatus according to claim 48 wherein the maps produced from scanning at least one surface of the material is combined with calibration curves to provide quantitative imaging of the material.

56. The apparatus according to claim 42 wherein the filtering means for filtering Planck-mediated emissions from the recombination-induced infrared emission includes a filter having a narrow spectral window that attenuates wavelengths in a wavelength band from about 7 to 12  $\mu\text{m}$ .

57. The apparatus according to claim 42 wherein the detection means is a room temperature solid state detector.

58. The apparatus according to claim 57 wherein the room temperature solid state detector is an InGaAs solid state detector.

59. The apparatus according to claim 42 wherein the detection means is a cooled solid state detector.

60. The apparatus according to claim 42 wherein said detection means is a multi-element array detector to rapidly image a large surface area of the surface of the material.

61. The apparatus according to claims 42 wherein said detection means is a single element detector.

62. The apparatus according to claim 60 wherein said multi-element array detector produces a signal array processed under parallel lock-in detection by oversampling the array at least four times per period, manipulating by sine and cosine modulation factors the elements of the array, storing them under in-phase and quadrature labels, and combining to construct demodulated lock-in amplitude and phase photocarrier radiometry (PCR) images of the array.

63. The apparatus according to claim 52 wherein said laser is a solid state laser.

64. The apparatus according to claim 63 wherein said solid state laser is modulated by current modulation.

65. The apparatus according to claim 52 wherein the laser is a gas laser.

66. The apparatus according to claim 42 wherein the excitation source is one of an electron beam source, a flashlamp, a light emitting diode (LED), or any other electromagnetic wave source, which produces a photon beam having sufficient energy to excite carriers in the semiconductor or optical material.

67. The apparatus according to claim 42 wherein the excitation source means is modulated by a mechanical chopper.

68. The apparatus according to claim 42 wherein the excitation source means is modulated by an acousto-optic modulator.

69. The apparatus according to claim 42 wherein the excitation source means is modulated by an electro-optic modulator.

70. The apparatus according to claim 42 wherein the detection means includes a filter for blocking the energy beam from the excitation source from irradiating the detection means.